Department of Electrical and Computer Engineering, Cornell University

---

ECE 3150: Microelectronics

Spring 2015

Lab 1 **Due one week after your lab day in the course "Lab Dropbox"**

Lab Goals

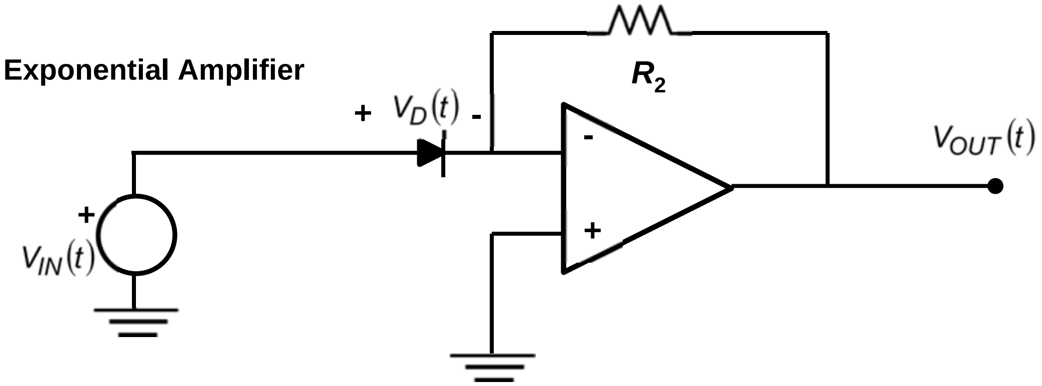
1) Get familiar with the 3150 lab and learn how to perform automated IV data acquisition with SMUs in the lab
2) Develop diode models for both large signal and small signal environments
3) Obtain diode model parameters from the measured data
4) Examine a simple diode circuit with small signal and large signal AC stimulus
5) Explore how the small signal circuit model is dependent on the DC bias of the diode
6) Examine harmonic generation from a non-linear circuit (exponential amplifier) using the FFT feature on the oscilloscope

Pre-Lab Work

In this lab you will be testing PN diodes. The most commonly used equation for the current vs voltage (IV) characteristics of a PN diode is:

$$I = I_o\left(e^{\frac{qV_D}{\eta KT}} - 1\right)$$

Here, η is a number, of the order of unity, that is called the diode non-ideality factor (typically, between 1 and 2). The non-ideality factor arises from effects, such as electron-hole recombination inside the depletion region, whose detailed discussion is beyond the scope of ECE 3150.



Exponential Amplifier

1.1 The Exponential Amplifier (A Non-Linear Circuit)

A linear circuit (or system) is one which outputs the same frequency as the one which is fed to the circuit (or system). In other words, a linear circuit does not generate any new frequencies. A non-linear circuit (or system), in contrast, can generate frequencies other than the one fed to the circuit. The exponential IV curve of a PN diode can be used to build interesting non-linear circuits. Consider the op-amp circuit shown above. This is an exponential amplifier.

a) In the limit of large op-amp gain (ideal op-amp), and assuming that the diode is always heavily forward biased, the output voltage is related to the input voltage as follows:

$$V_{OUT}(t) \approx -A\, e^{\frac{qV_{IN}(t)}{\eta KT}}$$

Find the value of the constant A above (assuming that the diode IV characteristics are described by:

$$I = I_o \left(e^{\frac{qV_D}{\eta KT}} - 1 \right)$$

b) Now suppose that the input voltage has a DC offset and an AC part:

$$V_{IN}(t) = V_{IN-DC} + v_{in-1} \cos(\omega t)$$

A circuit that produces a signal only at frequency ω at the output when the input signal has frequency ω is called linear. A non-linear circuit produces signals at frequencies different from ω at the output when the input signal has frequency ω. These other signals at different frequencies at the output in a non-linear circuit are typically unwanted and result in signal distortions.

In case of the exponential amplifier, the output voltage, given by the relation above, will not only have a DC component and an AC component at frequency ω, it will also have AC components at all frequencies $n\omega$ where n are integers, 1, 2, 3, 4…… These different frequencies are called harmonics of the fundamental frequency ω. For the exponential amplifier, the output voltage can be written as,

$$V_{OUT}(t) = -A\, e^{\frac{qV_{IN}(t)}{\eta KT}} = V_{OUT-DC} + \sum_{n=1}^{\infty} v_{out-n} \cos(n\omega t)$$

Your job is to find the values of V_{OUT-DC} and v_{out-n} in terms of the quantities A and $\eta KT/q$.

You will find the following expansion helpful:

$$e^{a\cos(b)} = I_0(a) + 2\sum_{n=1}^{\infty} I_n(a)\cos(nb)$$

Here, $I_n(a)$ are the "modified Bessel functions of the first kind". They are pre-programmed in matlab and can be accessed using the "besseli" function:

$$I_n(a) = \text{besseli}(n, a);$$

All bessel functions $I_n(a)$ are increasing functions of their argument a for $a > 0$.

c) Suppose,

$$V_{IN-DC} = 400\,\text{mV}$$
$$v_{in-1} = 100\,\text{mV}$$
$$\eta = 1.8$$
$$KT/q = 25.8\,\text{mV}$$

Find the ratios, v_{out-n}/v_{out-1}, for $n = 2,3,4,5$ in dBs (decibels), i.e. find the numerical values of,

$$10\log_{10}\left(\frac{v_{out-n}^2}{v_{out-1}^2}\right)$$

Lab Preparation

1) Carefully review this document. You need to know all that you will be doing in the lab and all the data that you will need later (after the lab) for the post-lab work.
2) You can use a USB memory stick to get data out of the lab computer (recommended). Or you might also be able to email the data files to yourself (not recommended).
3) Be sure to understand the analysis of the circuit to be built (pre-lab work).
4) Make sure you have had nice big lunch! But not big enough to put you to sleep in the lab!!
5) Examine the lab bench. There are 2 SMUs per bench. The upper instrument is at address 5 and the lower instrument is at address 7.
6) Go over the diode data sheet (on the course website). We will be using a silicon pn junction diode number 1N914A.
7) Review the op-amp chip (number LF353) data sheet (on the course website) which includes its wiring diagram.

Lab Work

1.2 Diode Current-vs-Voltage (IV) Curve Measurement

In this problem we connect the diode to a SMU for automated measurement of its current-vs-voltage, or IV, curve.

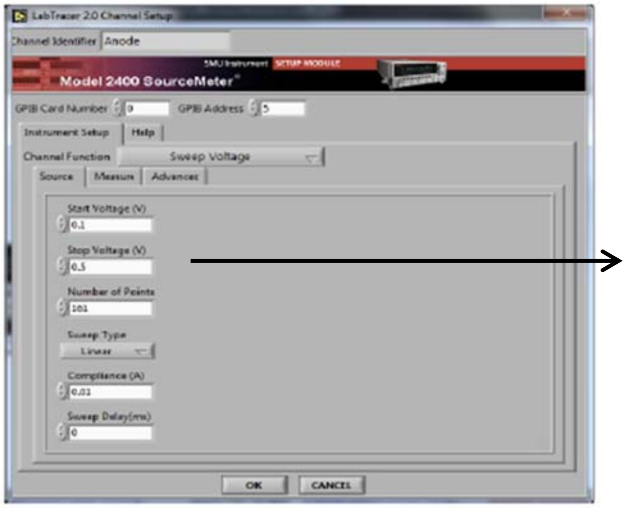
Place a 1N914A on your newly acquired proto-board and wire the diode anode (P-side) to the positive lead (red banana output) of the upper Keithley 2400 SMU (address = 5). Wire the diode cathode (N-side) (the side with the colored band) to the SMU ground (black banana output).

Start the Keithley software for controlling the SMUs (**Labtracer 2.0**). Be patient as the program loads. Wait for a window to appear as shown below in the Figure below.

Labtracer 2.0 (main window)

This software loads the measurement instructions that were last used by the program by default. Be sure that the 2400 instrument is loaded - click on the instrument image to select the 2400 SMU. Select the Setup 2400 found under the image of the instrument. Now a series of tabs can be selected to load measurement parameters.

Select the "Source" tab. The appearance of the window with the "Source" tab selected is shown below in Figure below.



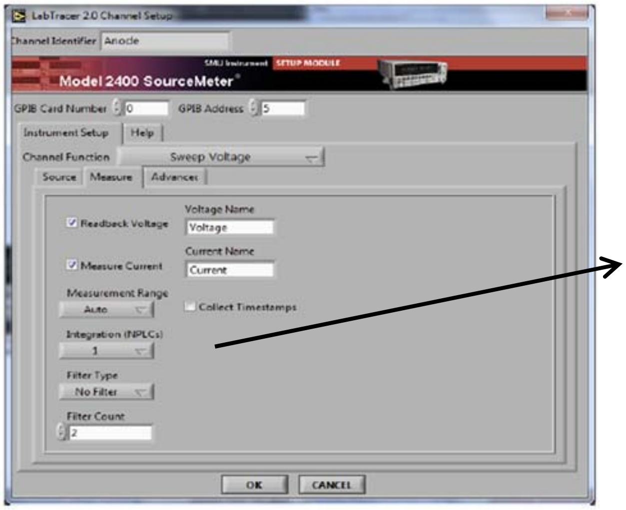
Channel Identifier: Anode
GPIB Card Number: 0
GPIB Address: 5
Channel Function: Sweep Voltage
Start Voltage (V): 0.1
Stop Voltage (V): 0.5
Number of Points: 161
Sweep Type: Linear
Compliance (A): 0.01
Sweep Delay(ms): 0

Start voltage: 0.1V
Stop voltage: 0.5 V
# of points: 161
Sweep type: Linear
Compliance: .01 A
Sweep delay: 0 ms

Labtracer window after the "Source tab" has been selected

In this window we select the channel function (Sweep Voltage in this case) and the starting voltage, the stopping voltage, and the number of data points in between. Input the numbers which appear in Figure into the program. The current compliance is also set to 10 mA as shown. Note that we are sweeping the diode bias voltage over a range of small forward bias only. Also note that the instrument GPIB address (5) appears in the upper center portion of the window. Press "OK" when done.

Now select the "Measure tab". The appearance of the window with the "Measure" tab selected is shown below in Figure below.



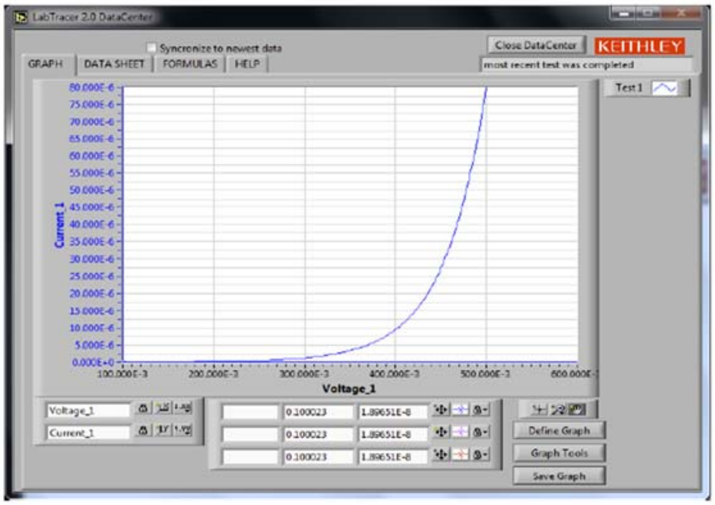
Channel Identifier: Anode
GPIB Card Number: 0
GPIB Address: 5
Channel Function: Sweep Voltage
☑ Readback Voltage
Voltage Name: Voltage
☑ Measure Current
Current Name: Current
Measurement Range: Auto
☐ Collect Timestamps
Integration (NPLCs): 1
Filter Type: No Filter
Filter Count: 2

Integration: 1
Filter type: No filter

Labtracer window after the "Measure tab" has been selected

In this window we select what is to be measured (both current and voltage in this case). The integration time also appears in this window and is set to an intermediate value of 1. The Filter option is not in use for this lab. Press "OK" when done.

Strike the "RUN TEST" button and the measurement begins. When completed (approximately 20 seconds) the "DataCenter" window appears as shown below in Figure.



most recent test was completed

Voltage_1
Current_1

0.100023 1.89651E-8
0.100023 1.89651E-8
0.100023 1.89651E-8

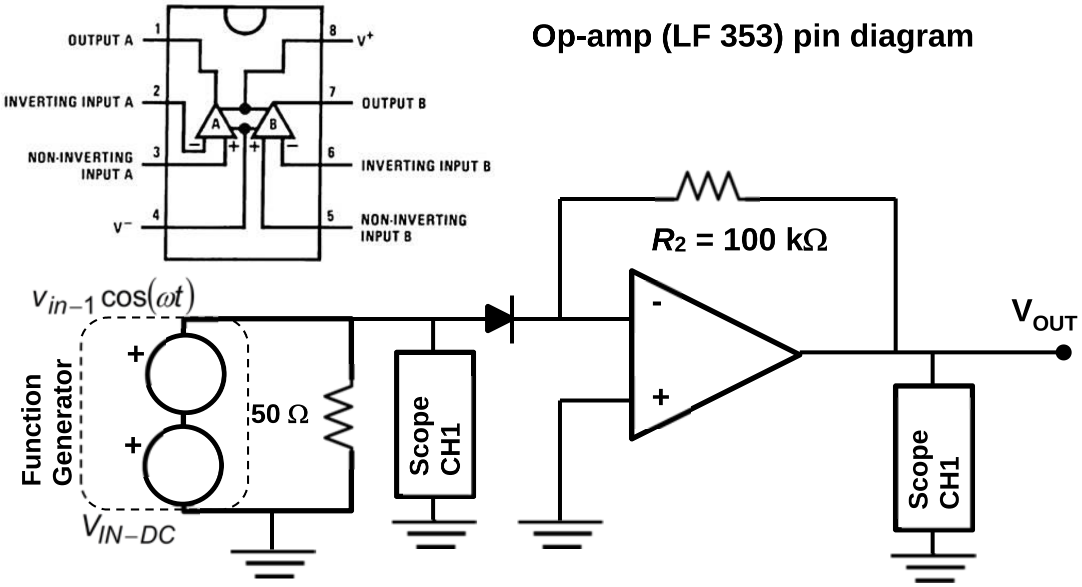
Labtracer DataCenter window

If the test went well, the diode's IV curve should appear as shown. If you don’t see any plot, click the “Define Graph” button to select the variables to be plotted. Get help from a TA if your data is not similar to what is shown in Figure above.

a) Strike the “DATA SHEET” tab and the measured IV data appears in a two column format. Striking the “Save Data” tab (lower right hand corner) will create a data file (ASCII) which you will store in a folder with your name in the documents folder and eventually on your memory stick. This file will be used in the lab analysis. So be sure that you saved it well.

1.3 Large Signal Operation

Build the diode test circuit shown below in the Figure. This is an exponential amplifier. Use +12 V DC supply for the V+ terminal and -12V DC supply for the V- terminal. Record the measured resistor (R2) value using the digital multi-meter (DMM) (it might not be 100 kΩ) and record it for later analysis.



Op-amp (LF 353) pin diagram

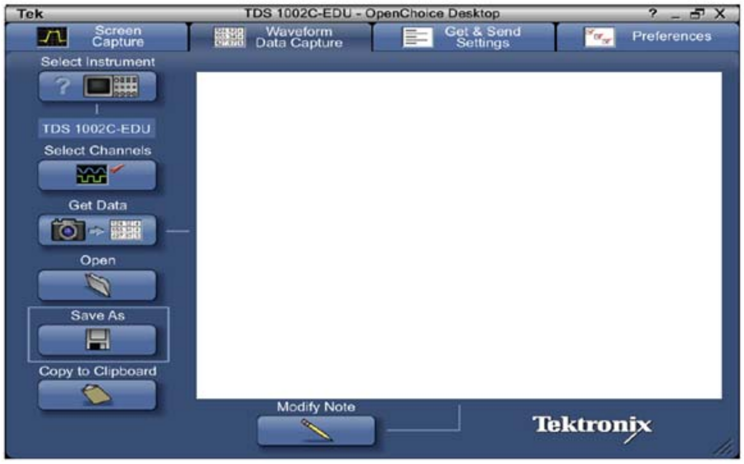
The function generator is used as the input voltage source providing both an AC signal $v_{in-1}\cos(\omega t)$ and a DC offset bias V_{IN-DC}. Attach the scope probes to both the input and output of this circuit. Be sure a 50 Ω load is placed in parallel with your circuit (load on the BNC-tee at the output of the function generator). Initialize the function generator by striking the Store/Recall button and selecting the ece2100 (not ece3150) setup. This will enable the external sync signal to be used to trigger the oscilloscope and it will select a 50 Ω load (which represents our measurement environment).

The function generator settings should be as follows: frequency is 250 Hz, the signal amplitude is 200 mV peak-to-peak (i.e. $v_{in-1} = 100\,\text{mV}$), and the DC offset is set to 400 mV ($V_{IN-DC} = 400\,\text{mV}$).

Set up the oscilloscope so the input and output waveforms are visible on the screen. Both channels should be on DC coupling, and each zero voltage position (with its associated color marker on the left hand side of the display) should be on the vertical center of the display. Since this is a 250 Hz input signal (with a corresponding 4 msec period), select 1 msec/div for the horizontal time axis. According to your analysis, the input voltage is always positive and the output voltage is always negative so each waveform will not overlap the other (provided the zero voltage position is the same for each channel).

a) Enable scope measurements on each channel for the maximum and minimum voltages. From these measurements determine the following input voltage parameters: 1) the DC offset V_{IN-DC} and 2) the AC amplitude (v_{in-1}). It would be a good idea to enable the data averaging feature by depressing the "Acquire" button and setting the averaging to 128. This will reduce noise in the measured waveforms. Record these values. The measured voltage values could differ from what you set them to be. Record these values.

Large Signal Waveform Acquisition:
Waveform acquisition is performed by running the "Tek OpenChoice Desktop" program from Textronix (the scope manufacturer) and installed on the desktop. A window should appear similar to the Figure below.



Tek OpenChoice Desktop window

First click the "Select Instrument" button and choose the USB0:xxx interface. Next click the "Select Channels" button and check both channel 1 and channel 2. Finally, select the "Waveform Data Capture" tab and then click the "Get Data" button. After a few seconds the waveforms should appear on the window. If they do not, get help from the TA before proceeding.

b) All that remains to be done is saving your waveform data. Click the “Save” button and place the data file in your folder in the documents folder (and/or your memory stick). Make sure your understand the format in which data is being stored. Get help from TA if you don’t.

Large Signal FFT Acquisition:
To display the FFT press the red “Math” button on the scope. Be sure the waveforms are displayed prior to selecting the “Math” mode. Leave the scope's signal averaging in place. The channel must be selected (channel 1 or channel 2) and the type of window used for the FFT calculation (in this case we are interested in the best amplitude resolution so we select “Flattop”). Using the horizontal scale rotary knob, select the horizontal scale to be 250 Hz/div. Using the vertical scale rotary knob, select the vertical scale to be 10 dBs/div.

When viewing channel 1 (the sinusoidal input signal), since the signal is not distorted, only the fundamental frequency component should be visible as a sharp peak at 250 Hz. When viewing channel 2 (the distorted output signal), sharp peaks should be visible every 250 Hz from the fundamental (250 Hz) up to the 4th harmonic at 1 kHz. In case, you don’t see the 4th harmonic, try increasing the DC offset voltage (V_{IN-DC}) to a higher value, say 450 mV. If you do see the 4th harmonic at the higher value of the DC offset then keep this value of the DC offset for the parts that follow and continue. If you do not see the 4th harmonic, get help from the TA. You can damage the diode if you increase V_{IN-DC} too much.

c) Now return to the computer and the “Tek OpenChoice Desktop” program. With either channel's FFT is displayed on the scope, click on the “Select Channels” button and check the “Math” box. Next with the “Waveform Data Capture” tab selected, click the “Get Data” button and wait a few seconds for the FFT to appear on the Program's window. Click the “Save” button and place the data file in your folder in the documents folder (and/or on your memory stick). Save a separate data file for both channels. The data is in the format of frequency in (Hz) followed by the relative spectral amplitude in units of **decibels**.

1.4 Small Signal Operation

We now want to examine the diode in the exponential amplifier circuit (shown above) under small signal conditions. This is accomplished by reducing the amplitude of the AC signal from the function generator from 200 mV peak-to-peak to 5 mV peak-to-peak (so the AC signal is indeed small). Do this gradually while viewing the FFT of channel 2 (the output). It is a good idea to turn off signal averaging in the scope so the scope's response time is small. As the AC signal amplitude is decreased the response should become more linear and the harmonics that you had seen should slowly disappear.

a) You should observe that while you are decreasing the AC signal amplitude, the highest order harmonic peak drops out first and then each of the remaining highest order peaks drop out in turn. When the second harmonic peak at 500 Hz drops out, the only remaining response is the fundamental (at 250 Hz) and at this stage the output response is approximately linear. Observe and record the AC signal amplitude setting on the function generator which corresponds to the onset of linear operation.

b) Record the measured values of the DC and AC input and output signal amplitudes with the 5 mV peak-to-peak setting on the function generator. Return to a timebase sweep (by pressing the yellow channel 1 button and resetting the horizontal scale to 1 msec/div). Initiate signal averaging at 128 and use peak-to-peak measurements. Note that AC coupling for both channels is useful for peak-to-peak measurements allowing scaling both the input and output signals to the maximum resolution. To measure the input bias voltage (V_{IN-DC}) remove the AC coupling from channel 1, rescale and measure the channel 1 mean voltage.

Increase the input voltage offset (V_{IN-DC}) on the function generator from 400 mV to 500 mV. Rescale the output signal display and repeat the small signal measurements (peak-to-peak) of the DC and AC input and output signals. Measure the new input bias voltage (V_{IN-DC}) by removing the AC coupling from channel 1, rescaling and measuring the channel 1 mean voltage.

Wind Down

Dismantle circuit and place your protoboard and the devices you tested in the bins which the TAs have provided. Transfer all generated files appropriately so you can access them on your computers outside this lab. Alternatively, if you brought portable media (memory stick) then gather up all files onto your media. You may leave files in your named folder but there is no guarantee that they will remain.

Post-Lab Work

1.5 Diode Current-vs-Voltage (IV) Curve

a) Fit the diode equation,

$$I = I_o\left(e^{\frac{qV_D}{\eta KT}} - 1\right)$$

to your measured IV curve acquired in lab work 1.2. Assume $KT/q = 25.8\,\text{mV}$. "Fitting" means finding the values of the parameters I_o and the ideality factor η that best fit your measured IV data. You need to plot your data and the fit obtained from the equation above on a log-current (with logarithmic ticks) versus linear-voltage set of axes. For clarity, the data should be plotted as a dashed line and the diode equation fit as a solid line. Compare the measured data with the diode equation fit and comment.

1.6 Large Signal Input and Output Waveforms

a) In lab work 1.3 (a) and 1.3 (b) you acquired the input and output waveforms (under a large input AC signal). From your pre-lab work, and the measured DC and AC input signal values, you can numerically find the output waveform using,

$$V_{OUT}(t) \approx -A\, e^{\frac{qV_{IN}(t)}{\eta KT}}$$

Now plot and compare the measured output waveform over one complete time period to the output waveform generated using the above equation in a single plot. Use a dashed line for the measured output waveform and a solid line for the computed output waveform. Comment on how well (or how bad) they compare.

1.7 Large Signal Input and Output FFT Spectra

a) In lab work 1.3 (c), you acquired the FFT spectra of the input and output signals (in dB). Using your recorded FFT data, make a plot of:

$$10\log_{10}\left(\frac{v_{out-n}^2}{v_{out-1}^2}\right)$$

such that the x-axis is the harmonic number n ($n = 1,2,3,4,5$) and the y-axis corresponds to the values in dB of:

$$10\log_{10}\left(\frac{v_{out-n}^2}{v_{out-1}^2}\right)$$

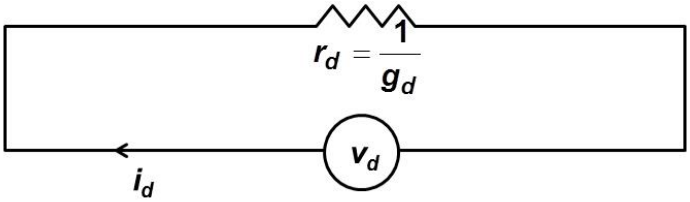
On the same plot, indicate the values in dB of the quantity,

$$10\log_{10}\left(\frac{v_{out-n}^2}{v_{out-1}^2}\right)$$

that you can calculate using results from the pre-lab work 1.1 (c) but this time use the measured (or fitted) value of the diode ideality parameter η from lab work 1.5 and the measured values of the input signal values. Compare the measurements and theory.

1.8 Small Signal Measurements: Diode Differential Resistance

The simplest small signal model of a PN diode consists of a differential resistance, as shown in the lecture handout,



Here,

$$\frac{1}{r_d} = \frac{\partial I_D}{\partial V_D}$$

a) From the measured IV curve of the diode in lab work 1.2, find the differential resistance and plot it as a function of the bias voltage. What is the differential resistance of the diode at the input DC bias voltage that you used in the op-amp circuit (which would likely be around $400\ \text{mV}$)?

1.9 Small Signal Measurements: Circuit Gain

a) Make a small circuit model of the op-amp exponential amplifier and then derive an expression for the small signal voltage gain,

$$A_v = \frac{v_{out-1}}{v_{in-1}}$$

b) In lab work 1.4 (b) you had measured the input and output AC voltages (peak-to-peak) at two different bias points (two different values of V_{IN-DC}). Calculate the voltage gain at these two bias points from your measured values. These are your measured voltage gain values. Now use the expression derived in part (a) and your results from lab work 1.8 (a) and again calculate the voltage gain at these two different bias points. This is your calculated (or predicted) voltage gain. Compare the measured and predicted values of the small signal voltage gain.